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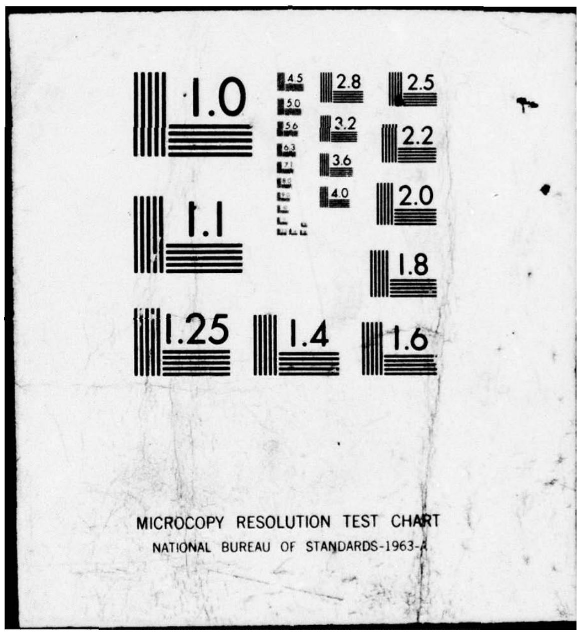
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I. INTRODUCTION

This project has involved a broad investigation of the propagation characteristics of acoustic waves in inhomogeneous anisotropic media, with special emphasis on focusing and beam steering and an evaluation of potential device applications of the phenomena. Attention was directed particularly at the possibilities for realizing electronically-controlled focusing and scanning of acoustic beams, functions of interest in applications such as acoustic spectrometry and acoustic imaging. The possibility of constructing an acoustic microscope was just beginning to arouse interest at the time of inception of this project, and one of the initial aims of the research was to evaluate the feasibility of an electronically scanned acoustic miscroscope.

The acoustic wave control functions described above are most readily provided by introducing appropriate inhomogeneity and anisotropy into the acoustic medium, and a theory of acoustic wave propagation in inhomogeneous anisotropic media was therefore needed to study them. At the frequencies of interest in microscopic imaging the acoustic wavelength is very much smaller than the dimensions of the laboratory system, and it is appropriate to use the short wavelength (or geometrical acoustics) approximation in studying this problem. A suitable formalism for this purpose is the Hamiltonian treatment of anisotropic optics.

In acoustic wave propagation, two kinds of inhomogeneity and anisotropy are relevant. First of all, there is elastic inhomogeneity and anisotropy. Low acoustic loss at kilomegacycle frequencies is found only in single crystal materials, which for the most part exhibit elastic <u>anisotropy</u>. Such materials may be made inhomogeneous by means of nonuniform doping. Another kind of anisotropy arises from coupling of the acoustic wave with another mode of the system (the control mode). If the strength of coupling varies with the direction of propagation the characteristics of the coupled, or hybrid, modes are anisotropic. This occurs, for example, in magnetic crystals, where the interaction anisotropy is due to magnetostrictive coupling of acoustic waves with spin waves,[1] and in piezoelectric semiconductors where there is piezoelectric coupling of acoustic waves with carrier waves.[2] Interaction inhomogeneity may be introduced by imposing a spatial variation upon some parametric which controls the properties of the interaction. In the case of the spin wave interaction this occurs naturally when the sample is nonspherical and the internal dc magnetic field varies spatially because of the demagnetizing effect.[3,4] In the cases of both elastic and interaction anisotropy, there are two basis mechanism available for focusing and scanning operations:

1. Refraction, which results from spatial inhomogeneity of either the control mode properties or the strength of its coupling with the acoustic mode, and
2. Group Velocity Deflection, which results from anisotropy of either the control mode properties or the strength of its coupling with the acoustic mode.

Investigation of bulk acoustic wave focusing and deflection by the above mechanisms was restricted to the case of magnetoelastic waves in yttrium iron garnet. The theoretical part of this work covered studies of magnetic deflection characteristics of collimated and focused acoustic beams, ray plot trajectories for focusing coil geometries and magnetoelastic delay lines,[2] and an evaluation of the operational characteristics of an acoustic microscope using a scanned focused acoustic beam as a probe. Experimental studies were made of collimated beam deflection, and focusing in a magnetic delay line. This research showed that strong acoustic focusing occurs in a magnetoelestic delay line, but that the group velocity deflection technique in a ferromagnetic medium does not provide a very satisfactory method for scanning a focused acoustic beam. Under other contract support, similar conclusions were reached for the scanning of a focused beam in a piezoelectric semiconductor.

The next phase of the program was concerned with the control of both surface and bulk waves by means of acousto-optical interactions in piezoelectric photoconductors. Because acoustic waves in a piezoelectric medium are accompanied by an electric field, they are sensitive to changes in conductivity and may be influenced by optical illumination of a medium that is both photoconductive and piezoelectric, or of a photoconductor contiguous to a piezoelectric medium. Studies of this effect under the present contract have been concerned with situations in which optical illumination is used to generate patterns of conductivity with dimensions comparable to an acoustic wavelength - for example, linear gratings in the case of surface waves and Fresnel zone plates in the case of bulk waves. Structures of this kind call for a diffraction optics, rather than a geometric optics, approach to the theory. Normal mode techniques have been shown to be a powerful tool for analyzing surface wave problems of this type, and standard optical diffraction theory is easily adapted to bulk wave zone plate problems. In the case of surface acoustic waves, experiments on surface-to-surface and surface-to-bulk wave scattering at a photoconductive grating were found to agree with theoretical predictions, and surface wave transduction with a spatially uniform electric field was obtained by superposing a photoconductive grating. Fresnel zone plate focusing of a bulk wave transducer was realized by placing a photoconductive layer contiguous to the transducer and then illuminating it with an optical zone plate pattern.

The successful demonstration of a Fresnel zone plate transducer addressed and controlled by an optical pattern motivated an in-depth investigation of zone plate transducers as imaging devices. Acoustic Fresnel zone plates have important practical advantage as acoustic focusing elements - they are of essentially zero thickness, have a frequency-controlled variable focal length, and can be designed to give super-resolution. Furthermore, they differ sufficiently from optical zone plates, in that they are typically constructed from one or more layers of finite thickness and have zones of imperfect opacity, that they pose a number of interesting problems in applied physics. Two non-photoconductive types of Fresnel-type transducers were constructed and tested under this program. One was a homogeneous bulk wave transducer excited by a set of Fresnel zone configured electrodes, and the other was an inhomogeneous transducer in which the inhomogeneity consisted of Fresnel zones with alternately positively and negatively polarized piezoelectric coupling. Both types of transducer were extensively studied, including the effect of the spatial frequency response of the transducer plate on the diffraction pattern, and experimental results were found to be in good agreement with the theory. These types of transducer were also used in acoustic imaging experiments at 10 MHz, giving the very nearly predicted resolution limit of 1.5 wavelengths in water.

In the concluding period of the contract a study was made of techniques for electronically scanning the focused beam and also of the effect of quarter-wave matching layers on the width of the focused spot.

II. MAGNETIC FOCUSING AND SCANNING OF ACOUSTIC WAVES

One of the goals of this project was to show the feasibility of using the ray equations to analyze wave propagation in inhomogeneous anisotropic media. A ferrimagnetic medium was chosen because there is a strong interaction between the acoustic waves and the spin waves, which enables large refraction and deflection effects to be obtained by means of the mechanism discussed in previous status reports. Furthermore, the strength of this interaction is a function of the applied magnetic field, which permits electronically controlled inhomogeneities to be introduced by means of spatial variations in the applied field. This leads to variable focusing and deflection of the acoustic waves. The particular ferrimagnetic material YIG was chosen because it has low loss characteristics for acoustic waves and spin waves, thus making the performance of experiments feasible as well as computer simulations. Furthermore, the magnetically variable delay line, a device involving magnetoelastic wave propagation, already existed and provided an interesting application of the ray theory method of analysis.

The delay line analysis showed that focusing of the magnetoelastic energy occurs in the Strauss-type delay line configuration.[5] It should be noted that the use of the ray theory imposes certain constraints on wavelength and the rate of change of the wave vector,[6,7] which are not completely satisfied at all points on the delay line ray plots. Therefore, the results must be considered as a first approximation subject to correction for diffraction and higher order effects. Nevertheless, the ray approach was especially helpful for characterizing the given delay line structures as either focusing or defocusing. An important conclusion is that profiles leading to linear delay dispersion for pulse compression applications[8] are focusing. It was also found that the ray paths can change from focusing to defocusing as the dc magnetic field distribution in the delay line is changed. An equation was derived which defines the initial refraction for any given field profile and leads to the specifications of the field distribution for minimum ray refraction. A perturbation technique can then be employed to study the character of the rays as the field distribution is changed from a focusing to a defocusing configuration.

A new approach to the generation of spin waves in magnetoelastic delay lines was developed. Although it was not possible to obtain quantitative results, the ray approach provided considerable insight into the mechanism by which a magnetostatic wave might convert into a spin wave. By restricting the analysis to a stratified medium it proved possible to utilize the wave vector surface to demonstrate the conversion process. For a realistic situation it would be necessary to consider the coupling from a wave theory viewpoint, including loss and the interaction with electromagnetic waves. Nevertheless, the stratified medium analysis, considered in conjunction with the experimental results,[9] pointed strongly to the conclusion that spin waves are generated by magnetostatic waves, which are in turn excited at the end of the rod by a transverse rf magnetic field.

Characteristics of the acoustic beam generated by a Strauss-type delay line configuration were measured experimentally, and the resonated half power width of the beam was found to be about 7 mils. Since the magnetostatic waves are known to fill almost the entire cross-section of the rod,[10] which typically has a diameter of the order of 100 mils, these experiments confirm that strong focusing of the energy takes place. Attempts to show that the focal plane of the beam could be changed by varying the magnetic field were not conclusive, but there was some indication that the position of the focal plane varied as a function of the magnetic field.

One of the most important reasons for detecting the beam experimentally was to determine if the beam could be scanned by changing the angle between the axis of the YIG rod and the direction of the magnetic field. However, the beam power was found to decrease too rapidly with angle to observe any significant deflection of the beam.

Another aspect of the work was the use of ray theory analysis to investigate the characteristics of magnetic scanning of a prefocused acoustic beam by varying an applied uniform magnetic field.* This type of deflection was predicted theoretically and observed experimentally in the case of a collimated beam. Analytically it was found to be impossible to scan a prefocused acoustic beam over enough spot diameters to produce an image, because of the distortion of the focal spot resulting from the scanning process. If the diameter of the diffraction limited spot size is about 30 wavelengths, and the largest dimension of the distorted beam is to be less than 60 wavelengths, then the beam can only be scanned over 10 spot diameters.

Acoustic beam focusing in a delay line, which was discussed above, is caused by the natural demagnetizing field variations in the YIG rod. It was also shown analytically that acoustic beam focusing can be produced by nonuniform magnetic fields that are generated externally by means of coils concentric with the YIG rod. In this method of focusing a trade-off between the amount of attenuation and the spherical aberration is necessary. The spherical abberation can be

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*This is a different arrangement than the magnetoelastic delay line where, as discussed in the previous paragraph, deflection was not observed experimentally.

made comparable to that of a simple optical lens, but at the cost of high attenuation. The attenuation, which is 40 dB for a 1 cm focal length, is the chief drawback of this type of magnetic lens.

Although a number of different aspects of magnetoelastic and acoustic wave propagation in YIG rods were studied, some topics were not taken as far as they could have been. No attempt was made to develop a workable device from a scanning element used in experimental work on collimated beams.[11]

At the present time, based on both analytical and experimental results, it does not appear that YIG is very suitable for focusing an acoustic beam or for scanning a prefocused acoustic beam. It should be emphasized, however, that the work done on the problem of focusing an acoustic beam was not exhaustive. Some type of periodic focusing may prove to have the low attenuation, low spherical aberration characteristics which are desired.

Finally, it should be pointed out that the ray theory method of analysis proved to be an excellent way to analyze magnetoelastic wave propagation in an inhomogeneous anisotropic medium. The analysis of the wave propagation in this type of medium would not be feasible by any other techniques except in the very simple geometries. The ray theory is also applicable to the analysis of wave propagation in other types of media. It has been used in the Microwave Laboratory to study the propagation of acoustic waves in semiconductors[12] where there is a strong interaction with the plasma waves which are present. There is also a very complete literature concerned with the application of ray theory to the propagation of light waves through various types of nonuniform media, to electromagnetic waves through the atmosphere and to seismic waves through the earth. Generally speaking, the ray theory method of analysis has proven to be effective in analyzing wave propagation in most situations where the inhomogeneities of the medium occur over distances which are large compared to a wavelength. This is a type of problem which occurs frequently in studies of wave propagation in solids at microwave frequencies and consequently, in this field there should be a wide range of applications for this method of analysis.

Further details of this part of the research are given in the following publications and reports.

II(a) B. A. Auld and J. H. Wilkinson, "Geometric Optics of Acoustic Waves in Magnetic and Piezoelectric Media," pp 203-218, Proc. Symp. on Modern Optics, Polytechnic Press, Brooklyn (1967).

II(b) R. C. Addison, B. A. Auld, and J. H. Wilkinson, "Electrically Controlled Acoustic Beam Deflection," Proc. IEEE 55, 68-77 (1967).

II(c) R. C. Addison Jr., B. A. Auld and J. H. Collins, "Raypath Trajectories in Magnetic Delay Lines," J. Appl. Phys. 38, 1217 (1967).

II(d) R. C. Addison, B. A. Auld, and J. H. Collins, "Ray-Theory Analysis of Magnetoelastic Delay Lines," J. Appl. Phys. 39, 1828-1839 (1968).

II(e) R. C. Addison, "A Ray Theory Analysis of Magnetoelastic Wave Propagation in Ferrimagnetic Media," M. L. Report 1777 and PhD Dissertation, July 1969.

II(f) B. A. Auld, "Magnetostatic and Magnetoelastic Waves," M. L. Report 1756, May 1969 (Applied Solid State Science 2, 1-106, Academic Press Inc., New York 1971).

II(g) R. C. Addison, B. A. Auld and D. C. Webb, "Focusing and Scanning of Acoustic Waves in Solids," Acoustical Holography 2, 117-132, Plenum Press 1970.

III. EVALUATION OF THE PERFORMANCE CHARACTERISTICS OF A SCANNING ACOUSTIC MICROSCOPE

As a continuation of the evaluation of the applicability to acoustic microscopy of scanning and focusing in YIG, discussed in Section II above, a fundamental comparison was made of the operational characteristics of a scanned acoustic imaging system with other acoustic imaging systems and with optical and scanned electron beam systems. In a scanned acoustic microscope an acoustic image is formed by scanning a small focused beam across the object and detecting either the transmitted or reflected energy. An image is then constructed by displaying the received signal on a cathode ray screen. At 1 GHz the acoustic wavelength in water is approximately 1.5 microns and the ultimate resolution comparable to that of an optical microscope. Detailed calculations of contrast sensitivity showed, however, that as much as four orders of magnitude increased in contrast sensitivity over an optical instrument is to be expected. This is due to the superior sensitivity of a microwave receiver compared with any type of optical detector. A correspondingly large improvement in sensitivity obtains with respect to the scanned electron beam microscope, although in this case the electron microscope has far superior resolution. Because of these unusual characteristics a scanned acoustic microscope can be extremely useful for examining biological specimens and for flaw detection in small opaque objects; and, in fact, such an instrument has now been developed using techniques different from those discussed here.[13]

Details of this part of the contract research are given in the following publications and reports.

III(a) B. A. Auld, "Geometrical Acoustics at Microwave Frequencies, Semi-Annual Status Report No. 5," Stanford M. L. Report No. 1642 May 1968.

III(b) R. C. Addison, B. A. Auld and D. C. Webb, "Focusing and Scanning of Acoustic Waves in Solids," Acoustical Holography 2, 117-132, Plenum Press 1970.

IV. CONTROL OF ACOUSTIC WAVES WITH OPTICALLY INDUCED INHOMOGENEITIES IN PHOTOCONDUCTIVE MATERIALS

Certain piezoelectric materials, such as CdS, CdSe, ZnO and ZnS, are also photoconductors, and this effect may be used to optically control the transduction of a bulk wave transducer, over either its entire surface[14] or scanning it point by point.[15] Under this contract other methods for using optically illuminated photoconductive transducers to scan and focus acoustic beams were studied.

Several promising prospects existed in the surface wave area. In the conventional interdigital surface wave transducer on a piezoelectric substrate a spatially periodic electric field is generated by means of a very closely spaced array of finger electrodes. For efficient excitation the spacing of the electrodes must match the wavelength of the surface wave. If a photoconductive piezoelectric substrate is used, the required spatial periodicity in the exciting field can be achieved by using a uniform electric field and then illuminating the substrate with a periodic array of light and dark stripes. This introduces a spatial periodicity in the conductivity, which then produces the required periodic electric field. The advantage over the finger structure is that there is no actual physical structure and the spacing can therefore be varied at will by changing the light pattern. Also, the surface wave beam can be scanned by rotating the pattern and focused by using an illumination pattern with curved light and dark stripes. All of these variations are easily varied, in some cases continuously.

Processing of bulk wave beams with illuminated photoconductive transducers is also possible. An obvious example is a Fresnel zone plate lens. As is well known in optics, such a lens consists of an aperture comprising a series of annular shaped openings (or Fresnel zones) with appropriately chosen dimensions. The light transmitted through these openings interfers constructively to produce a principal focus at a point on the axis determined by the dimensions of the rings. In acoustics the same effect may be produced by illuminating a photoconductive transducer with an optical Fresnel zone pattern. In the illuminated regions the acoustic radiation is suppressed (or shadowed) by the photoconductive effect and the interference focusing effect occurs as in optics. Since the size of the optical illumination pattern can be varied at will, such a transducer can operate with adjustable focal length.

Not all of the possibilities discussed above were actually investigated under this program. In the area of surface wave interactions surface wave transduction, as well as surface-to-surface and surface-to-bulk scattering were studied. The most suitable material for this purpose was considered to be cadmium sulfide. Since a suitable crystal of photoconducting CdS was not available, an 0.5 μ evaporated film was used on a YZ-cut lithium niobate substrate. This had the incidental advantages of providing both efficient interdigital transducers for the surface wave and low acoustic propagation loss. The principle uncertainty before these experiments was the question of whether or not the carrier diffusion length in an evaporated film would significantly limit the minimum periodicity achievable in the photoconductive pattern.

The first surface wave experiments involved measurements of acoustic attenuation due to uniform illumination of the film. Using a lw pulsed argon laser as the light source an attenuation of 1 dB per wavelength was obtained at a surface wave frequency of 106 MHz. The figure was used to estimate the surface wave "impedance" change $\Delta z/z$ at a transition from unilluminated to illuminated CdS . The value obtained ($|\Delta z/z| = 0.02$) was then used to determine the reflection from gratings of illuminated stripes. For direct back scattering from a 20-element grating the reflection coefficient obtained was between -5 dB and -10 dB , in reasonable agreement with theoretical predictions. Ninety degree scattering from an angled grating was also observed. Allignment and positioning of the grating mask used to produce the illumination pattern was found to be quite critical. A similar experiment involving photoconductive scattering of surface into bulk waves was then performed, after the development of a Born perturbation analysis of such problems. This was based on a normal mode theory[16] in which the secondary waves generated by the photoconductivity perturbation can be evaluated through normal mode expansion techniques. This procedure is applicable to either surface-surface or surface-bulk scattering. In the experiments the same optical source and grating pattern were used as above and a comparison was made of surface-surface scattering with surface-bulk scattering, the latter being detected by a bulk wave transducer on the bottom of the substrate. The experimental ratio of bulk scattering to surface scattering was - 38 dB in good agreement with the theoretical value of - 37 dB . The final experiment of this series, involved generation of surface waves by applying a tangentical electric field across a photoconductive grating. A one-way conversion efficiency of - 27 dB was obtained at 106 MHz .

Several experiments were performed on photoconductive Fresnel zone plate transducers operating at 1.5 GHz . The structure consisted of a thin film transducer of photoconductive CdS evaporated onto a sapphire delay line and illuminated with the desired Fresnel zone pattern, using the same pulsed argon laser as in the surface wave experiments. A ten-zone pattern was employed, giving a first zero in the theoretical focal plane diffraction pattern at a radius of 37 μm . In the initial experiments, focusing was observed by means of a small fixed transducer (of 250 μm radius) at the opposite end of the delay line. This allowed observation of an increase in transmission when the focal length was adjusted to the length of the delay line. It did not permit accurate measurement of the focal spot diameter by transverse displacement of the zone plate, because of the large size of the output transducer used as a probe. More accurate measurements were achieved by using a water suspension of polystyrene balls to visualize the focal plane distribution. The nonlinear acoustic response of the water generates a static force distribution that causes the balls to position themselves in a pattern corresponding to the impressed acoustic field.[17] A low power microscope was used to observe this distribution. Results were in reasonable agreement with the theory. However, these photoconductive Fresnel plate transducers were not suitable for imaging because the conversion efficiency was low. Subsequent study of Fresnel plates involved other structures.

Details of the research on photoconductive control are furnished by the following publications and reports.

IV(a) B. A. Auld, D. A. Wilson, D. K. Winslow and E. Young, Jr., "Control of Acoustic Surface Waves with Photoconductive CdS Film," Applied Physics Letters 18, 339-341 (1971).

IV(b) G. Chao, "Time-Variant and Microwave Acoustic Signal Processing," Stanford PhD Dissertation, September 1971.

IV(c) G. Chao, B. A. Auld and D. K. Winslow, 1972 Ultrasonic Symposium Proceedings, pp 140-141 IEEE Publication 72 CHO 708-8 SU.

IV(d) B. A. Auld and S. A. Farnow, "Coupling of Surface and Volume Acoustic Waves by a Photoconductive Grating," J. Appl. Phys. 45, 4315-4319 (1974).

IV(e) S. A. Farnow, "Acoustic Applications of the Zone Plate," Stanford M. L. Report 2499 and PhD Thesis, December 1975.

V. FIXED ZONE PLATE TRANSDUCERS

Because of the inefficiency of the photoconductive zone plate transducers described above and the technical difficulty of fabricating transducers for operation at 1.5 GHz , subsequent zone plate investigations were performed on fixed structures at frequencies in the range of 1 - 10 MHz . Two transducer configurations were studied. The first, which had been tried initially at 1.5 GHz , had transducer electrodes shaped in the form of a series of Fresnel zones. The second, used only at VHF frequencies, consisted of a PZT disk in which a Fresnel zone pattern is recorded by poling alternate zones of the transducer disk in positive and negative directions respectively. To explain the difference in operation and advantages of these structures it will be necessary to review briefly the main characteristics of zone plates as focusing elements.

The concept of a zone plate is based on the constructive interference of radiation from a series of circular regions (or zones). In an amplitude zone plate, corresponding to the first type of transducer mentioned in the previous paragraph, alternate zones are excited with equal amplitude and equal phase. A diffraction analysis at this kind of system shows that there exists an infinite series of real and virtual foci, plus a parallel undiffracted beam. In a phase reversal zone plate, which corresponds to the second type of transducer above, adjacent zones are excited with equal amplitude and 180° phase shift. This phase reversal suppresses the undiffracted beam, but all real and virtual foci remain. For both structures the distribution in the plane of principal focus, the one of interest in practical applications, consists of the focused beam plus a background made up of a superposition of smeared out contributions from the other focal terms plus the undiffracted beam. These other contributions lead to artifacts in imaging applications and it is an outstanding advantage of the phase reversal zone plate that it suppresses the undiffracted beam, a major factor in the creation of false images.

Fresnel plate transducers were constructed and operated in the frequency range of 7 - 10 MHz and were used for both transmission and reflection imaging of a variety of objects. In the transmission measurements zone plates were used for both transmitter and receiver. The best results were obtained with phase plate transducers, although even in this case care had to be taken to avoid spurious effects arising from the secondary foci. The best lateral resolution obtained was 0.27 mm at 10 MHz , which corresponds to $1.8\ \lambda$ and is in good agreement with theoretical predictions. The longitudinal resolution is determined by the Rayleigh range of the focused beam and is approximately 1 mm , in reasonable agreement with diffraction calculations.

The scanning function necessary for production of images by a focused beam was realized by mechanically scanning the object to be viewed. This has the disadvantage of slowness. In the case of longitudinal section imaging (B-scan), semi-electronic scanning may be realized by exploiting the property that the focal length of a Fresnel lens is proportional to the frequency. By driving a Fresnel transducer with a linear FM chirp one can thus electronically scan the focal point in depth. The lateral scanning required to complete the lateral section image can be performed mechanically by moving the object. Another technique, which allows electronic scanning in the lateral dimension as well, places a phased array grating electrode on the back of the zone plate transducer. This allows the focused beam to be sector scanned by suitably phasing the grating electrodes. An experiment was performed on this scanner structure and it was found that the results followed predictions out to a beam deflection angle of $\pm 3.3^{\circ}$. The primary technical problem in systems of this kind is to realize a broad transducer response in both temporal and spatial frequency. This requires the use of broadbanding techniques, to be discussed in the following section. An important theoretical problem requiring further attention is that of side and grating lobes. It was observed experimentally that the scannable zone plate transducer had unusually high lobe responses far off axis and these were also confirmed in a preliminary diffraction calculation. The latter indicated that careful attention would have to be given to the dimensions of the grating electrodes for optimum performance.

The following detailed publications relate to this aspect of the program.

V(a) G. Chao, B. A. Auld and D. K. Winslow, "Focusing and Scanning of Acoustic Beams with Fresnel Zone Plates," 1972 Ultrasonic Symposium Proceedings, pp 140-141, IEEE Publication 72 CHO 708-8 SU.

V(b) S. A. Farnow and B. A. Auld, "Acoustic Fresnel Zone Plate Transducers," Appl. Phys. Letters 25, 681 (1974).

V(c) S. A. Farnow and B. A. Auld, " An Acoustic Phase Plate Imaging Device," Acoustical Halography 6, 259-273 Plenum Press 1975.

V(d) S. A. Farnow, "Acoustic Applications of the Zone Plate," Stanford M. L. Report No. 2499 and PhD Thesis, December 1975.

VI. SPATIAL FREQUENCY RESPONSE OF A ZONE PLATE TRANSDUCER

In the Fresnel plate transducer discussed above focusing is obtained by applying a spatially nonuniform distribution of excitation to a transducer disk in such a way that the acoustic radiation produced interferes constructively at some point in front of the transducer. To fully understand the detailed operation of such transducers it is necessary to consider the transfer relation between the applied voltage distribution $V(x,y)$ across the piezoelectric and the resulting radiated pressure distribution $P(x,y)$ for the case of a transmitter, or the transfer relation between the incident pressure $P(x,y)$ and the resulting voltage distribution $V(x,y)$ in the case of a receiver. Only the latter case, which is simpler to analyze will be described here. One proceeds by performing a two-dimensional Fourier transform of the pressure field $P(x,y)$ of the acoustic image and seeking to relate each Fourier (or spatial frequency) component of pressure at the input to a corresponding component of the voltage distribution at the output. The importance of having a broad spatial frequency response in a Fresnel plate transducer is easily understood by noting that high spatial frequency components represent plane waves arriving at the transducer at large incidence angles. It follows, then, that the resolution of the transducer, which is related to its angular acceptance angle (or numerical aperture), can be increased by increasing its spatial frequency response. Conversely, a Fresnel zone plate transducer will not realize the theoretical resolution corresponding to the number of zones in its zone plate pattern unless the transducer structure itself has an equivalent spatial resolution capability.

Analysis of the spatial frequency response of our transducers was performed by a method developed by Ahmed et al.[18] Using this method, it was possible to show that the spatial frequency response may be radically improved by adding either a lossy backing plate behind the transducer or multiple $\lambda/4$ matching layers to the front face. These theoretical ideas were verified in a number of experiments. It was observed on one of our zone plate transducers without backing or matching layers that the distance to the first null of the focal plane distribution decreased from 0.64 mm at 8.4 MHz (10% above the fundamental resonance) to 0.22 mm at 10.4 MHz . This corresponded to a three-fold increase in resolution, but at a cost of more than 10 dB increase in sidelobe level. This is explained by the fact that operating above the fundamental resonance enhances the high spatial frequency response of the transducer at the expense of the low spatial frequency response. (See Publication VI(b)). A similar improvement in resolution, but without the sacrifice of sidelobe rejection, was achieved by backing the transducer with lead.

During the final year of this program, in addition to the scanned zone plate experiments summarized in the previous section, work was done on an air-backed phase reversal zone plate transducer with multiple quarter-wavelength matching layers on the front face, following the concepts developed in Reference 19 and in Publication VI(a) below. The matching layers in this case were a 0.0073" layer of pyrex next to the PZT-5A transducer plate and a 0.0025" layer of Scotch Tape (Magic Transparent No. 810) between the pyrex and the water delay medium. Material parameters were: Pyrex, $Z = 12.1 \times 10^5$, $V = 5.64 \times 10^5$; Scotch Tape, $Z = 1.74 \times 10^5$, $V = 1.5 \times 10^5$ in cgs units. This was not the correct combination for an ideally flat frequency response, and gave a theoretical transducer input impedance curve with peaks at approximately 5.5 and 9.0 MHz . The calculation was made using the Mason model for a uniform thin disk transducer - that is, neglecting the effect of the phase reversal zone pattern in the piezoelectric. Nevertheless measurements of the input impedance showed the two predicted peaks (at 6 and 10 MHz), but with a higher value of the input resistance between the peaks and an upward shift of the reactance curve. The latter anomalies were attributed to series resistance and reactance in the leads and comparison with measured insertion loss measurements supported this conclusion.

For the pulse echo insertion loss measurements the focused beam was reflected from a small diameter target at the focal point. Initially metal targets were used, but this was found to give a frequency response that depended upon the size and shape of the target, presumable due to internal resonances. Consequently, small rods of tungsten-epoxy (a highly loss material) were fabricated and used end-on as targets. The results obtained were found to be independent of rod diameter. Measured insertion loss was found to have minima of approximately 15 dB one-way at the two peaks of the input impedance curve. This was 8 dB greater than the theoretical value after allowing for a series resistance estimated from measurements of tin and for the fraction of total power delivered to the main focus.

Even in this rather imperfectly matched system the increase in bandwidth over an unmatched system was impressive. Measurement of the focal plane distribution of the front matched transducer showed that the beam width was equivalent to that obtained earlier with the lead backed transducer. In summary, it can be stated that the Mason uniform transducer model is adequate for calculating the effect of front matching layers, and that even an imperfect matching transformer configuration, such as the one used in our experiments, provides a marked improvement in the focal plane profile.

VI(a) B. A. Auld, M. E. Drake, and C. G. Roberts, "Monolithic Acoustic Imaging Transducer Structures with High Spatial Resolution," Appl. Phys. Letters 25, 479-480 (1974).

VI(b) S. A. Farnow, "Acoustic Applications of the Zone Plate," Stanford M. L. Report No. 2499 and PhD Thesis, December 1975.

VII. SUMMARY

The principal accomplishments of this research were

(1) Prediction and demonstration of tight focusing in YIG magnetoelastic delay lines (1966 - 1969).

(2) Demonstration of acoustic wave scattering by photoconductive gratings and development of analytical methods for problems of this kind (1969 - 1972).

(3) Demonstration of acoustic Fresnel zone plate focusing with photoconductive, metal electrode, and ferrelectrically poled Fresnel plate

transducer structures. Study of the fundamental properties of these transducers and performance of imaging experiments (1972 - 1976).

Of these, the Fresnel zone plate studies are considered to be the most significant and to merit further investigation. Although high quality images were obtained this imaging method has considerable difficulties with interference effects due to the other orders of diffraction, even in the phase reversal plate where the zero order diffracted beam is suppressed. This is a topic which needs further investigation, particularly with regard to other phasing patterns for the zone excitation. In connection with the scannable zone plate, further study of the sidelobe problem is required. There also exist possibilities for spiral scanning and pulse compression operation of zone plates. These are to be reported in a letter currently under preparation. In addition, a review article on acoustic zone plates is being written by Dr. Farnow, who is now employed by Texas Instruments.

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R. C. Addison, Graduated July 1969

G. Chao, Graduated September 1971

S. A. Farnow, Graduated December 1975.

REFERENCES

1. B. A. Auld, Applied Solid State Science 2, 1-106, Academic Press Inc., New York 1971.
2. D. L. White, J. Appl. Phys. 33, 2547 (1962).
3. W. Strauss, J. Appl. Phys. 35, 1022 (1964).
4. B. A. Auld, BSTJ 44, 495 (1965).
5. W. Strauss, J. Appl. Phys. 36, 118 (1965).
6. M. Kline and I. W. Kay, Electromagnetic Theory and Geometric Optics (Interscience, New York 1965) p. 10.
7. B. A. Auld and R. C. Addison Jr., IEEE Trans Sonics and Ultrasonics SU-13, 92 (1966).
8. J. Klauder, A. C. Price, S. Darlington, and W. J. Albersheim, Bell Syst. Tech. J. 39, (1960).
9. B. A. Auld, J. H. Collins and D. C. Webb, J. Appl. Phys. 39, 1598 (1968).
10. J. H. Collins and D. A. Wilson, Appl. Phys. Letters 12, 331 (1968).
11. R. C. Addison, B. A. Auld, H. J. Shaw and D. K. Winslow, "Acoustic Beam Deflection in YIG by a Magnetic Field," Appl. Phys. Letters 6, pp 196-198 (1965).
12. J. Wilkinson, PhD Thesis Microwave Laboratory Report No. 1679, Sept. 1968, Stanford University.
13. R. A. Lemons and C. F. Quate, Appl. Phys. Letters 24, 163 (1974).
14. B. A. Auld, D. C. Webb and D. K. Winslow, "Acoustic Beam Scanning by Optical Control of Piezoelectric Coupling," Proc. IEEE 57, pp 713-714 (1969).

15. B. A. Auld, R. J. Gilbert, K. Hyllested, C. G. Roberts, and D. C. Webb, "A 1.1 GH_2 Scanned Acoustic Microscope," Acoustical Holography 4, pp 73-96 Plenum Press 1972.

16. B. A. Auld, "Acoustic Fields and Waves in Solids," Vol II, pp 302-309, 314-315, Wiley-Interscience, New York 1973.

17. C. F. Quate, "Acoustic Interference in Solids and Holographic Imaging," Acoustical Holography, Vol. 4, 667-685, Plenum Press 1972.

18. M. Ahmed, R. L. Whitman, and A. Korpel, "Response of an Isotropic Acoustic Imaging Faceplate," IEEE Trans SV-20, 323 (1973).

19. C. G. Roberts, "Optically Scanned Acoustic Imaging," M. L. Report 2361 and PhD Thesis, October 1974.